

THE STATE OF PULSAR THEORY

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ABSTRACT

I summarize the status of pulsar theory, now 35 years after their discovery. Although progress has been made in understanding the relevant processes involved, there are several widely held misconceptions that are inhibiting further advances. These include the idea that plasma “must” be accelerated from the magnetic polar caps (the basis for the “Hollow Cone Model”) and the idea that winds would be driven away by centrifugal forces, with large amplitude electromagnetic waves playing no role whatsoever. However, recent theoretical work is converging on a picture that closely resembles the latest HST and CHANDRA images, providing hope for the future. No less than 3 groups have recently confirmed the early Krause-Polstorff-Michel simulations showing that the fundamental plasma distribution around a rotating neutron star consists of two polar domes and an equatorial torus of trapped nonneutral plasma of opposite sign charges. Unless a lot of new physics can be added, this distribution renders the Goldreich-Julian model irrelevant (i.e., along with most of the theoretical publications over the last 33 years).

HISTORICAL NOTES

Pulsar research is probably similar to a number of other fields, but it definitely has some distinctive characteristics. One characteristic, representative of the theorists, was shaped by the shockingly unexpected discovery of the radio pulsar phenomenon. Compact sources of intense radio emission were about the last thing theorists expected to be discovered. This led to the general expectation that the mechanism would have to be so extraordinary that, once exposed, would be obvious for all to see. This in turn lead to a feverish “race” to explain pulsars, with Tommy Gold being in the forefront with his model of bunches of charged particles being swung about a magnetized neutron star, and being confined out to the “light circle.” I personally was bombarded almost weekly with revised versions of another theory from a pair of theorists. This highly competitive atmosphere produced a rather disruptive research atmosphere where everyone went their own direction, which I will call here, for lack of a very clever name,

1. Searching for the quick kill (theorists). This general atmosphere probably resulted from people being drawn from diverse research backgrounds, who had therefore never collaborated before. Nevertheless, in fairly quick order the likely nature of the astrophysical object involved narrowed down to the rotating, magnetized, neutron star model of today. The major theoretical dispute was over the possibility that the stellar object might be a known object (a white dwarf, as favored by the “smart money” of the time) rather than the new and therefore exotic object, the neutron star.

Observers, on the other hand, while undoubtedly scrambling to be the first to discover the next pulsar (especially when the list stalled at four for a while), nevertheless seemed to be rather more collegial. And the observers seemed to believe that, with sufficient observation and analysis, they would be able to figure out how pulsars worked from observation alone. One might call this,

2. Maintaining community solidarity (observers). After all, the radio astronomy community had been around for some time prior to the discovery of pulsars, and ways of working together had been developed. The *relatively* cooperative and congenial attitude among observers can be illustrated by the idea that the magnetic fields of pulsars decayed with a period of a few million years. This idea was suggested around 1975 and pretty well became the accepted view among observers until perhaps 1995, even though few observers actually checked over the data to see if this claim could be supported. Finally, straightforward simulations showed that the data did not support magnetic field

decay on that short a time scale (see e.g. Michel, 1991a). It is curious that among the physics community, virtually no one believed in this rapid magnetic field decay, although there are to this day those in the astrophysical community that adore the idea (since it is, after all, plausible). The fact that this idea was so widely accepted in the observational community for so long illustrates the supportive atmosphere at work.

Another set of characteristics seem relevant. Among the theorists, a corollary to the first attitude is to

3. Exaggerate even the smallest incremental advance. It should be clear that this tendency is a direct consequence of the idea that the theoretical resolution of how pulsars work would be right around the corner. So “rounding” any corner naturally sparked huge excitement. And every such small advance usually lead to a publication announcing (“at last”) the definitive understanding of pulsars.

Meanwhile, the observational community came to be

4. Indifferent to theoretical disputes. Given the disarray among theorists, with each following their own idiosyncratic ideas, the observational community has understandably grown to think that little profit is to be had from sorting through the various disagreements among theorists. And this too is consistent with their underlying assumption that they would succeed in understanding how pulsars work on the basis of observation alone.

If one made a parallel to pulsar research with other research efforts like, say, the “war on cancer,” which seems to have dragged on a similar length of time, it would seem bizarre. Here we would have a handful of people (“theorists”) who sit in their offices with pencil and paper trying to figure out how cancer works, only one or two of whom would be funded at any one time, compared with numerous doctors (“observers”) who insist that, if they only could see enough patients, they would be able to figure out how cancer worked by themselves.

Finally, we should note that despite their importance,

5. Much of pulsar data are private. This contrasts with NASA sponsored research where spacecraft data is usually made available within a few years (ideally one year) of acquisition. But NASA does not run radio telescopes. I am not sure what the current situation is, but from experience, it has not been easy (i.e., possible) for most theorists to readily obtain and analyze radio observations of pulsars (I’ll now have to start to say “radio pulsars”).

In this regard I cannot help but think of E. K. Bigg, whose name will not probably ring a bell for many readers, but what he noticed may ring a bell. In 1964, Bigg published the astonishing observation that Jupiter’s decametric radiation was modulated by its innermost satellite Io. He discovered this entirely by fiddling with the data. It was entirely unexpected theoretically and seemed implausible to the observers.

But there will not likely be such a breakthrough for pulsars, since pulsar data is not only not available to amateurs, it is largely unavailable to theorists. Not that theorists necessarily have any special expertise. It is quite the opposite. Sometimes someone needs to ask a stupid question (could Io possibly effect radio emission from an entire planet, with the largest magnetosphere in the entire solar system?). The relative lack of interest by observers in theory works to a similar disadvantage. Smart people are not looking over these shoulders. No one will say, “you forgot to carry the one.” Of course if theory were to predict some definite correlation or the like, certainly observers would check it. But they are unlikely to go out of their way to check the theoretical underpinning. In other fields the experimentalists are usually as well informed as the theorists. It is just a division of labor.

I conclude this section with the following observation:

$$1967 + 35 = 2002.$$

So 35 years have passed. Will the way pulsars work yield to theory alone? Will it yield to observation alone? The numbers are not on anyone’s side. I will try to suggest why theory hasn’t done it yet. One reason was the chaotic approach to the problem, everyone running in different directions. The other is, paradoxically, how a strong line of conventional wisdom keeps people from looking in different directions, which we will next examine.

PULSAR RESEARCH IS NO LONGER “NEW”

It is worth noting that 35 years significantly exceeds the period where a topic can be safely considered “new.” One attraction of a brand new field is that one does not have to do much literature search. Almost any idea will be a new idea in the sense that no one was thinking about this topic before. However, after 35 years, the chances are high that any “new” idea will not actually be new.

6. No one can correctly assume that their “new” idea is actually new. In fact, this whole attitude was not strictly true even on “day one,” since related research areas may already have inspired related theoretical work.

Examples relevant to pulsars are Deutsch (1955), who published the electromagnetic fields expected surrounding a rotating magnetized star, and Piddington (1957), who suggested that the magnetic field of the nebula might be that of the wound-up field of a rotating central star. Of particular note is the paper by Hones and Bergeson (1965) who show that a rotating magnetized body will be surrounded by a plasma density

$$\rho = -\frac{\mu\omega}{2\pi cr^3} \left\{ [3\cos^2\theta - 1] \cos\gamma + [3\sin\theta\cos\theta\cos(\phi - \omega t)] \sin\gamma. \right\} \quad (1)$$

(their equation 17), where γ is the inclination angle of the dipole magnetic field. Here μ is the magnetic moment, ω is the stellar rotation rate, and the angles are the usual spherical angles. Their expression is therefore completely general and not confined to the special case that the rotation vector is aligned with the magnetization axis. And they point out that the consequence is that this plasma will rigidly rotate with the body (star, say). Indeed, they point out that these deductions (rigid corotation and a specific space charge density) were made much earlier by L. Davis, Jr. (1947, 1948). Thus the “modern” view that rotating magnetized neutron stars would be surrounded by plasma, for example, is anything but new. Four years after Hones and Bergeson, Goldreich and Julian (1969) proposed the same thing in regard to pulsars, restricting themselves to the trivial case of an aligned rotator, and adding the assumption that a wind would be generated at the light cylinder owing to centrifugal forces due to the rigid corotation. Unfortunately, this one innovation proves difficult to verify. Equally unverified is the supposition that such a wind demands in turn the replacement by new particles accelerated out of the magnetic polar caps.

Consequences

Nevertheless, these ideas permeate the pulsar field, possibly because the magnetic polar caps are clearly special places and therefore plausible sites of special activity. But the underlying model offered rather little in the way of explaining how pulsars might work.

- No pulses were actually produced (the model being restricted to the aligned case, although Hones and Bergeson gave solutions for the general case of arbitrary inclination).

- No reason for radio emission was supplied.
- No reason for coherent emission was supplied.
- No idea of the spectral distribution was supplied.
- No idea of any high-energy emissions was supplied.
- The model was unable to provide closed electric currents.
- The model was in fact shown to be incorrect (1980-1985)

The model was nevertheless quite popular since it was

- Easy to understand, and
- “Self-consistent.”

Polar Cap Acceleration (Observation)

The commonly accepted idea is that radio emission is beamed outwards from the magnetic polar caps, that must then be inclined relative to the spin axis of the neutron star so as to sweep a “lighthouse” beam through the sky and produce brief pulses as seen by distant observers.

This is the so-called “Hollow Cone Model,” based on this idea that particles are being accelerated out of the polar caps to replace those lost by a centrifugal wind at the light cylinder. This model was and is a very popular one among observers, and in fact it is used implicitly to infer the angle between the spin and magnetization axis as well as that between the spin and line-of-sight to the observer (usually denoted “ α ” and “ β ”). These angles are inferred by assuming that the magnetic field lines radiate radially (as projected on the surface) and that the polarization angle projected on the sky is fixed relative to the direction of those lines. Usually it is assumed that the polarization is either parallel or perpendicular, but orthogonal polarization jumps complicate the interpretation some. Figure 1 is now in many popular books, so it will probably be impossible to get this corrected even if, as we strongly suspect, this whole story turns out to be wrong.

Polar Cap Acceleration (Theory)

Exactly the same assumption has entered the theoretical work. If putative replacement from the magnetic polar caps is where the radiation comes from, then one should be able to zoom in on just the polar caps and ignore the rest of the system, Figure 2. Many theorists thereby ignored any aspect of the physics except that which might take place over the polar caps. But explicit simulation shows that there are no forces excited by this loss of plasma.

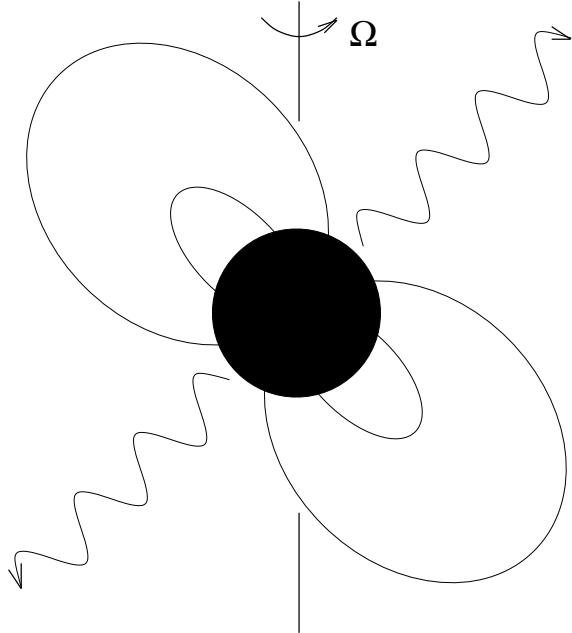


Fig. 1. Tilting the aligned rotator to get pulses. Wiggly lines represent the supposed origin of radio emission from the magnetic polar caps. Thin lines represent closed magnetic field lines near the neutron star (black sphere). Although clearly a generic model, the assumption here that the radiation is axially aligned with a dipole moment is manifest.

“Light Cylinder”

Among many curiosities is the endurance of the term, “Light Cylinder,” which was actually coined by T. Gold (1969) in connection with a model that no one believes any more. In that model, Gold had an ad hoc bunch of charged particles swung in a circle as fast as possible, namely at a distance $r = c/\Omega$ from the rotating star (we use an upper case Ω to underscore that this is a macroscopic quantity, unlike Hones and Bergeson (HB), who use ω). Goldreich and Julian (GJ) assumed that a plasma wind transition took place at the same distance and this term persisted, although it carries with it the direct implication that the physics of the pulsar system is somehow dominated by centrifugal effects above all else. In the same way, it has constantly been assumed in phenomenological papers that the magnetic field lines that went “to” the light cylinder were of special character. Typically the “Hollow Cone” in the model pertains to the locus of those magnetic field lines that reach out to the light cylinder. From symmetry, this would define a circle (the magnetic polar cap) for aligned rotation. Some papers try to “correct” for the shape of the polar caps when the magnetic dipole is inclined, since now a different set of field lines would be involved depending on the azimuthal direction of the field line, as shown in Figure 3.

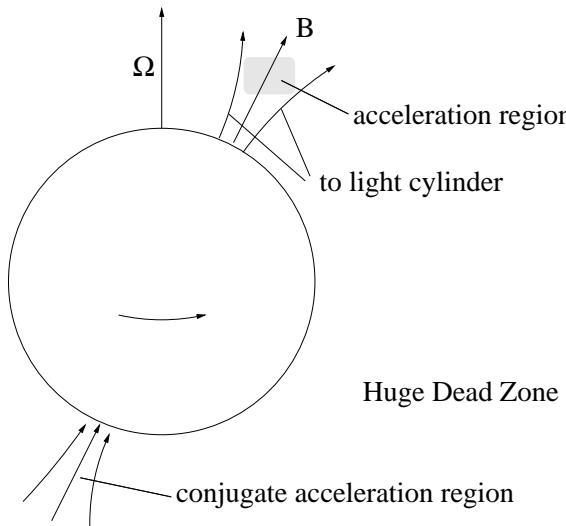


Fig. 2. Generic polar cap acceleration region, adapted from Michel (1975). The locus of field lines to the light-cylinder is taken to demarcate the polar cap which supposedly encompasses the field lines on which particles from the surface are accelerated. Remaining closed field lines enclose a huge corotating inactive zone.

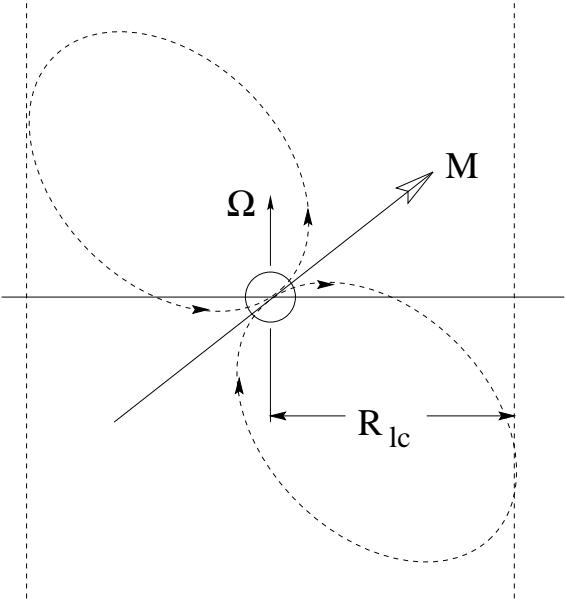


Fig. 3. Magical magnetic field lines that touch the light cylinder, adapted from Michel (1991a). Note the disparity in lengths of the field lines to the opposite sides of the polar caps.

The Polar Cap Acceleration Myth

What we have been discussing is the polar cap acceleration “myth.” It is a myth not because we can disprove that the radiation comes from the polar caps. It is a myth because the model that generated this idea is baseless.

Figure 4 shows the electrostatics above the polar cap of an aligned rotator. The basic electrostatics is simple to understand. First, it is quite true that an aligned rotator will act to pull charged particles up off the polar caps (and much of the rest of the star). But this is not the end of the story. It is easy to show that an aligned rotator will have an intrinsic electrostatic charge. For simplicity this charge is shown concentrated at the center of the star, although the exact distribution depends on the actual magnetic field structure inside the star. For a point dipole all the way to the center, the charge will be all at the center, which is the simplest case. The more complicated cases simply obscure the essential details that follow. The basic electrostatics is explained in detail in Michel (1991a) and in even more detail in Michel and Li (1999).

What the central charge does is attract back toward the star exactly the sign of charge that would be emitted over the polar caps. Basically, the field that leads to emission is quadrupolar in nature. This field is highly effective close to the surface, but falls off rapidly ($1/r^4$) and is overtaken by the monopole field ($1/r^2$) of the central charge. Thus particles moving along magnetic field lines *are* accelerated off the surface but they pass through a trapping surface and above that surface they are accelerated back towards the polar caps. By failing to notice this fundamental feature of the electrostatics of the aligned rotator, enthusiasts have assumed that the acceleration would act to infinity. In

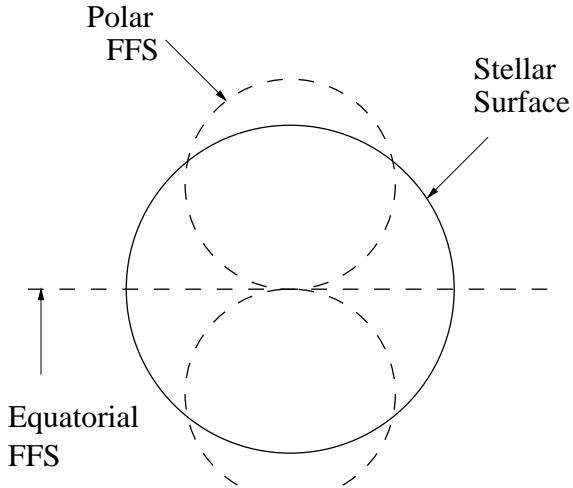


Fig. 4. Trapping surfaces of an aligned rotator, denoted here “FFS” for Force-Free Surface, from Michel and Pellat (1981). The \mathbf{E} field component parallel to \mathbf{B} reverses sign at an FFS, and therefore particles of one sign are pushed together (trapped) here, while the other sign are pushed away. The surfaces outside are independent of the surfaces inside, but are continuous as shown if the magnetic field is from a point dipole at the center.

Figure 4, the locus where the two balance is labeled “FFS Polar,” is drawn to scale, and shows how small the actual acceleration region is. The trapped particles accumulate on this force-free surface (FFS).

The contrary is easy to illustrate. In Figure 5 we sketch how an aligned rotator would be charged if it were a rotating sphere of laboratory dimensions.

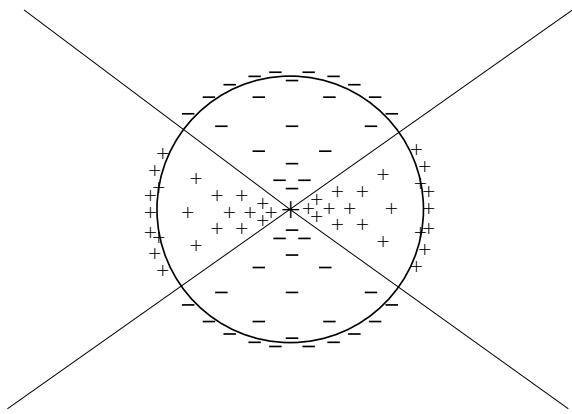


Fig. 5. Charge distribution on an “aligned rotator” in the laboratory. Here the magnetic dipole is at the center and there is a central charge (the slightly larger “+” at the center), space charge separation in the interior, and a trapped surface charge. All three components are required for $\mathbf{E} \cdot \mathbf{B} = 0$ in the interior. An arbitrary uniform surface charge could be added (e.g., to give a total charge of zero, say), since this charge would contribute no additional internal \mathbf{E} field.

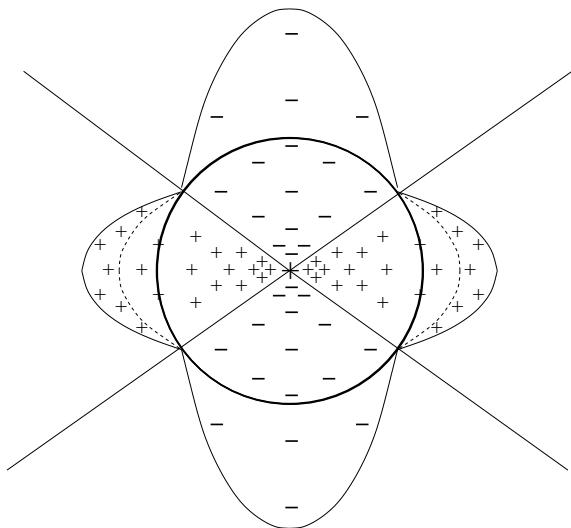


Fig. 6. Redistribution of charges in Figure 5 if the charges were to be released from the surface. The interior central charge and interior charge separation is unchanged, while the surface charge becomes a surrounding electrostatic shell (here the exact configuration depends on how much uniform surface charge was added).

It is easy to show that you will not get a “pulsar” by rotating a spherical magnet in the laboratory. It is still true that the system would accelerate particles off the surface, but the electrostatic fields (for achievable magnetic fields and rotation rates) obtained cannot overcome the work function of typical metals and consequently a surface charge appears but it cannot escape the surface. This surface charge is closely connected to the Hones and Bergeson (HB) space charge. Inside the star, this space charge is produced (technically it will be a charge-separation in the conducting material) along with the central charge. It is a simple calculation to show that these two sources of electrostatic field do *not* give $\mathbf{E} \cdot \mathbf{B} = 0$ inside the star. One also needs a third component which is the one that would have been provided by continuing the space charge on beyond the stellar surface to “infinity.” But there is no such space charge in the lab. It could only come from the rotating magnet, but the work function prevents that. So what the system has to do is instead accumulate enough *surface* charge to *do the same job*. What the interior of the star needs is three sources of electric field: (1) the central charge, (2) the internal charge-separation, and (3) a surface charge that provides exactly the same internal quadrupole electrostatic field that would have been supplied by filling the surroundings (since this is impossible) with the HB space charge. But this field can be provided just as well with a surface charge of the correct strength and distribution.

This is the point at which the Goldreich Julian model first and fatally goes wrong. There is no “obligation” that the space charge fill space around the rotating magnet. It is just an alternative solution that must be discarded if the physics will not allow it to happen. Here the work function interferes, and the system settles for a surface charge.

But we can always pretend that the work function is zero (in the laboratory, we could try to blast the surface charges off with laser beams or something). NOW do we get a pulsar? No, we get what is shown in Figure 6.

What has happened here is that, as advertised, surface charge released from the star goes out into the surroundings. But the surroundings are tightly constrained. The particles in the equatorial belt (assumed to be positive for

definiteness) will simply follow magnetic field lines out, and since they are tightly curved near the star, we can only form a narrow torus in this way. The charges above the polar caps could in principle follow magnetic field lines to “infinity,” but they encounter the trapping region. Whether or not any charges might make it to infinity is irrelevant since escaping particles only increase the total charge of the system, which makes it ever harder for further particle loss. All this says is that charge is conserved. If positive particles are all trapped in a torus, we cannot very well continuously lose negative charges. This criticism of the GJ model was well publicized (Michel, 1982) and the exact resolution of it (formation of trapped domes and torus) was suggested in Michel (1980), demonstrated explicitly in Krause-Polstorff and Michel (1985a,b: KPM), and summarized in Michel (1991a). Recent repeat simulations, plus a number of other numerical experiments (Smith, et al., 2001: STM) are fully consistent with the original ones. The generic distribution of plasma around an aligned rotator is therefore simply a dome and torus of oppositely charged particles. For the most part, this (finite) space charge density is that predicted by Hones and Bergeson back in 1965.

If one compares what should naturally be found over the magnetic polar caps (domes of trapped plasma) with what is so generally assumed even today (regions dominated by outgoing beams of accelerated particles), we see that the mismatch is shocking. Again, without a clear idea of how pulsars actually function, we cannot prove that the domes are not somehow stripped off and replaced by beams. But there is a big difference between wishing for something and actually having it.

Expanded work

It is awkward to insist that one’s own work is definitive, so we should note that the basics of this work have been repeated a number of times by others independently (Neukirch 1993, Petri et al. 2002, Shibata 1989, Spitkovsky and Arons 2002, Thielheim and Wolfsteller 1994, Rylov 1989, Zachariades, 1993). Indeed, this duplication points up the sociological point made in the Historical Notes: theory has had a tendency towards competition more than cooperation. Not one of these authors exchanged any communication with us saying that they were re-investigating the issue of trapped plasma around aligned rotators, or called our attention to their published results. Figure 7 shows a recent work using a completely different numerical routine that faithfully reproduces the KPM results.

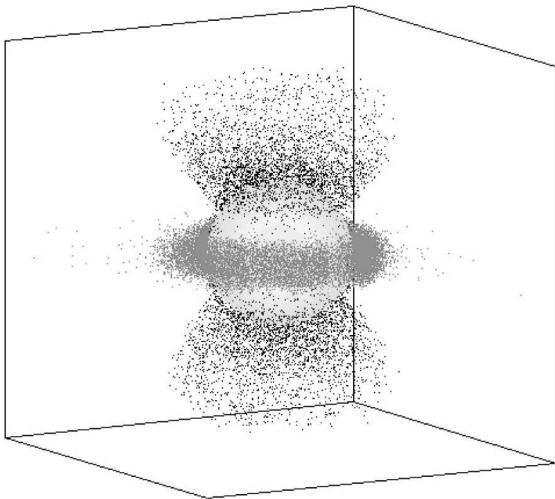


Fig. 7. Simulations by Spitkovsky and Arons (2002) reproducing Krause-Polstorff-Michel results. Again we obtain two domes over the dipole=spin axis and a torus of opposite charge girdling the equator.

The original KPM work has recently been entirely redone STM (2001) giving complete reproduction of the original results. This new code was used to additionally test some other issues. Two in particular are of interest, as we will next discuss.

GJ model failure

First, it should be evident from examination of Figure 6 that not only do the surroundings of an aligned rotator *not* fill with plasma, but that is an impossible solution if plasma has to follow magnetic field lines. There is then no way to get a torus to extend to large distances without having the particles somehow cross intense magnetic field lines (an issue we will return briefly to). At large distances, the positive particles would have had to come along magnetic field lines from surface areas where there could only be negative surface charges. But, we can numerically put charged particles wherever we want them, so as a numerical exercise in STM (2001), initial GJ configurations were created out

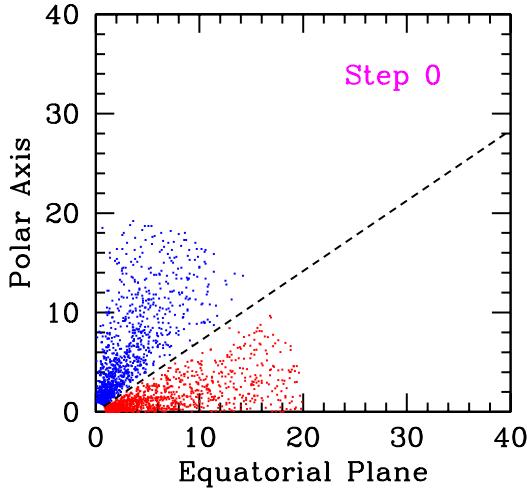


Fig. 8. Goldreich-Julian configuration at start of simulation. The configuration was arbitrarily truncated at $r = 30$, since the problem is largely scale invariant. The configuration already looks somewhat like a dome and torus owing to the HB charge density going to zero along the dotted line (which therefore separates charges of opposite sign).

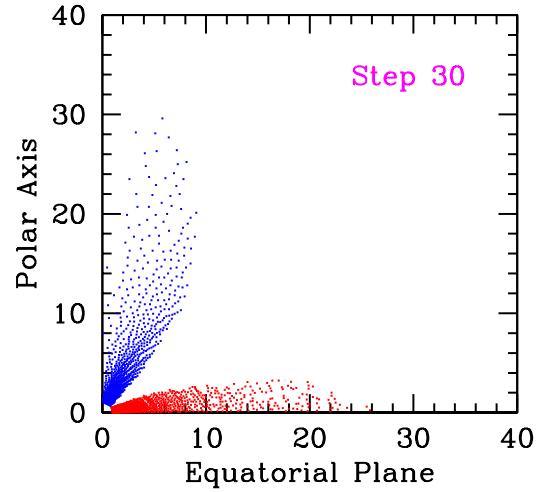


Fig. 9. Goldreich-Julian configuration at end of simulation (about 30 steps). There is no action to pull “replacement” charges from the magnetic polar caps. A color movie showing the evolution is available at <http://spacsun.rice.edu/~ian/gj pulsar/>. There, blue particles above and red particles below represent the two signs.

to large distances and then allowed to relax (since they do not correspond to natural solutions to the aligned rotator, they are not in static equilibrium for *any* finite size). When they relaxed, they immediately fell apart to form domes and tori as shown in Figure 8 (pre-collapse) and Figure 9 (fully collapsed).

Putting this another way, there is no obligation whatsoever for plasma to be replaced. The idea that a “wind” would be spun off at the “light cylinder” is irrelevant because there is no plasma extending to this distance (unless of course other physics is put in). And it is irrelevant even if a wind removed plasma, since there is no obligation that it be replaced. *The argument that there must be acceleration of particles from the polar caps to replace loss at large distances is baseless.* If particles are accelerated off polar caps, it will be for some other reason. At present, it is a myth. Historically, it should be noted that even earlier it was shown that a purely aligned rotator could not work (Scharlemann, et al., 1978), but this was based on a different physical constraint and did not answer the question of what would happen if aligned. This question was answered in KPM.

Pair production

The possible role of pair production has been an interesting one, and we find it very attractive (Michel 1991b) because it could explain how charged bunches would form naturally and thereby account for the coherency of pulsar radiation. One role of pair production might be to provide ionization outside of the neutron star and thereby help “fill” the magnetosphere as imagined in the GJ model (although these authors were clear in their assumption that the magnetospheric particles all came from the surface). Although something like this should be possible (owing to the huge $\mathbf{E} \cdot \mathbf{B} \neq 0$ regions between the domes and the tori) STM (2001) show that the consequent filling of the domes and tori reduce this source and would turn it off. Moreover, for typical pulsars where the magnetic field at the famous light cylinder would be only of the order of a few gauss, pair production would have no chance of operating. Pair production was suggested in the first place only because the pulsar magnetic fields were so large at the surface.

FrankenModels

To reprise, a simple aligned rotator should have domes and a torus. In between would be a huge vacuum gap. It was suggested on the basis of such gaps that high-energy emissions might develop in such gaps from the Crab and Vela pulsars (Cheng, et al., 1986). This is exactly what was just discussed above, some sort of discharge activity between the dome and torus. Ironically, when Cheng, Ho, and Ruderman introduced this gap model for the Crab pulsar, they cited KPM as justification.

This today has lead to what one might call “FrankenModels” after the pieced-together (from ill-fitting bits) monster in Mary Shelley’s novel. Here we find models in which radio emission comes as ever from the polar caps, and *additionally* high-energy emission comes from vacuum gaps. But the gaps, *contradict* the idea that there is activity just above the polar caps. And if there were activity over the polar caps, it would presumably be because the gaps had been filled in and (somehow) permit GJ activity. A classic example of wanting to eat the cake and still have it too.

Custom Gaps

In much the same way, the fact that CHR more or less postulated gaps has lead to the idea that gaps are somehow a customizable feature that can be added in whatever size and location that would be handy. This of course is completely at odds with the search for models that are physically self-consistent. Some of this seems to stem from an early paper by Holloway (1973) where a simple explanation for the possible existence of gaps is given (Michel 1991a). This paper is usually cited by proponents of gamma-ray emission coming from gaps, which is physically inconsistent: the reason for such gaps is that they cannot fill *unless* a local source of ionization were present (i.e., a putative gamma-ray generation activity), which would then close them and turn off the activity. See “FrankenModels,” above. Holloway never seems to have realized, as we (and others now) claim, that the gaps vitiate the GJ model, but assumed that the gap only consisted of a tiny separation along the zero charge line (locus of $\mathbf{B} \cdot \boldsymbol{\Omega}$) (see Holloway and Price 1981).

CENTRIFUGAL PREOCCUPATION

Another huge distortion of the likely physics has been the idea that pulsar action is ruled by centrifugal force. This idea is certainly a plausible one if one believes that a plasma wind is “spun off” from a pulsar and “requires” the replacement of plasma from the magnetic polar caps. But as we have seen, neither a centrifugal wind nor an acceleration region to replace the wind particles results from the basic physics. Worse, it is essentially impossible to drive currents of both signs with centrifugal force. This conclusion should not be a surprise. After all, centrifugal force is an inertial force that acts on bodies proportional to their mass and independent of their other properties (e.g., charge). The problem is that plasma surrounding even an aligned rotator does not “know” that the star is spinning. All the charged plasma particles experience are the local electromagnetic forces. Of these forces, the electrostatic force is dominated by the monopole moment of the central charge, which drops off as

$$E_r \approx \frac{1}{r^2} \quad (2)$$

while the magnetic field will be dominated by the dipole

$$B_\theta \approx \frac{1}{r^3} \quad (3)$$

and consequently the drift velocity will be azimuthal and scale as

$$V_\phi = \frac{E_r}{B_\theta} \approx r. \quad (4)$$

The “light cylinder” will be whatever the distance r is that $V_\phi = c$.

So far, so good, but what about the “centrifugal forces spinning off a wind?” The problem is that once beyond this magical distance, the electric field will dominate for the simple reason that particles cannot go faster than c . But a monopole will accelerate away only one sign of charge. And charge conservation forbids endlessly spinning off only one sign of charge. So the whole notion that centrifugal winds will spin off a wind collapses. Also the idea that the centrifugal forces become “infinite” at the light cylinder distance is physical nonsense. The largest forces will be of the order of eE .

Wave Fields

The simplest resolution to the problem (of how charges of both signs can be lost) is that the dominant forces are really the electromagnetic wave fields. It comes as no news to the observational community that the neutron star magnetic fields should be inclined to the spin axis. How else to have “the searchlight?” The idea of centrifugal dominance comes only because it is assumed that the aligned rotator would function as a pulsar. If not, inclination would also be necessary to activate the pulsar action. Indeed, it is unlikely that the magnetic field of a neutron star could be so perfectly aligned and purely dipolar that there would be no wave fields whatsoever at the wave zone.

The effect of wave fields is to accomplish that which is incorrectly attributed to centrifugal forces: drive off a wind of either charge. In a wave field we have

$$E_\phi \approx \frac{1}{r} \quad (5)$$

and

$$B_\theta \approx \frac{1}{r} \quad (6)$$

giving

$$V_r \approx \frac{E_\phi}{B_\theta} \rightarrow c, \quad (7)$$

which is independent of charge.

Unlike centrifugal forces, there is a quasi-spherical *wave zone* at essentially the same distance as the light cylinder, but no cylinder. From an inclined pulsar, circularly polarized waves race up the spin axis to accelerate out plasma there as well as out the equatorial axis. If we examine the Crab pulsar, as shown in Figure 10, we see that the overall topology is essentially that of a torus and two domes, with this now representing a wind, so that the domes now appear to be jets shooting out of the spin axis.

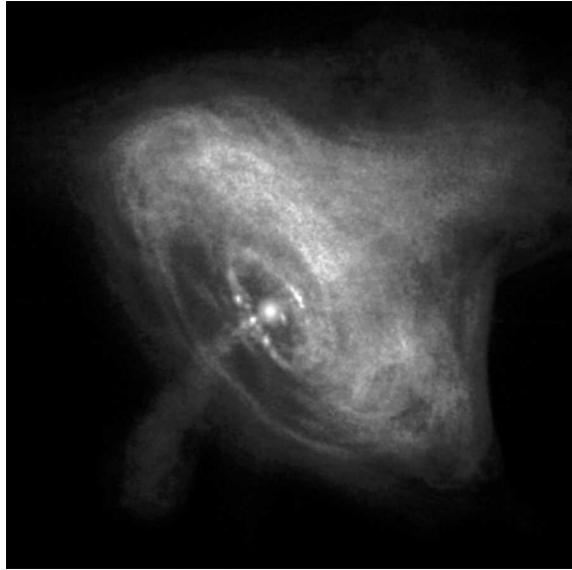


Fig. 10. X-ray image of the Crab Nebula from CHANDRA. Note how the equatorial distribution of wisps and the polar jets exactly mimic the domes and torus distribution expected about a rotating neutron star.

If correct, this interpretation would suggest huge charge separations driven by equatorial outflows of one sign of charge and polar jets of the other sign, which in turn might account for the one jet that is clearly starting to turn back to the nebula at its outer reaches.

“NEW” IDEAS

As noted in the Historical Notes, 35 years is too long for anyone to assume that an idea new to them is new to the field. Some explicit examples follow.

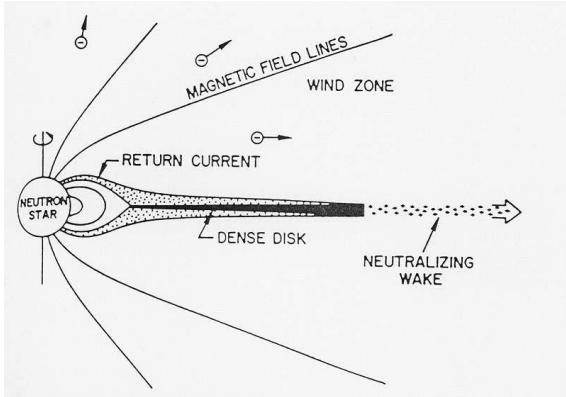


Fig. 11. A material disk surrounding a rotating neutron star, which would provide an electrical short through the closed field lines. Activity would be essentially ensured.

Pulsar Disks

Recently, a spate of papers have appeared suggesting that timing inconsistencies in pulsars could be accounted for by a “fossil” disk around the neutron star (ordinary albeit degenerate matter, as opposed to a disk of nonneutral plasma), as illustrated in Figure 11 (Alpar et al., 2001, Menou et al., 2001, Marsden et al., 2001, Perna et al., 2000). But not only is this not a new idea (Michel and Dessler, 1981, 1983, 1985, and Michel, 1991a), but even the putative source of the disk (supernova fall back) is not even new (Michel 1988). A fossil disk is one of the few dynamic elements that could be added to a neutron star without being excluded by timing measurements.

This idea actually originated in an attempt to explain pulsar action in view of the failure of the GJ model. A disk would be natural in that one would have two elements in an electric circuit (the neutron star and the disk) that could not be corotating and therefore could not be at the same potentials. Some sort of discharge would certainly be plausible, and the later papers addressed issues such as “could the disk last along enough.” The term “fossil” disk is itself not even new.

Presumably it is only a matter of time before someone is bold enough to suggest that disks are indeed needed for pulsar action *per se.*, which will then not be a new idea.

Concluding Remarks

A number of new physical issues are coming to the fore.

Nonneutral Plasmas

Most astrophysicists or physicists are not taught nonneutral plasmas. There are relatively few sources Davidson (1990), Michel and Li (1999), Michel (1982, 1991a). Yet nonneutral plasmas are the natural plasmas to be found around strongly electrified objects like rotating neutron stars, simply because the huge electric fields tend to stratify the plasma (as in producing domes and tori) and selectively pull out plasma (from conducting surfaces) of only one sign.

The fact that the plasma surrounding a rotating magnetized neutron star should be arranged in the form of domes and tori should be understood as a fundamental one which would have to be explicitly modified if one were to find a structurally different configurations (such as accelerating gaps over the polar caps) instead of simply being ignored because it doesn’t fit preconception.

Importance of Large Amplitude Electromagnetic Waves

As discussed in Michel and Li (1999), wave acceleration can be highly efficient *along* magnetic field lines such as along the spin axis of a pulsar. The energetic jets seen from the Crab pulsar are quite possibly evidence of this basic physical fact. Such jets would not be due to astrophysical “nozzles,” as is almost universally the assumption, but rather do to preferential acceleration where the magnetic fields do not form obstacles (i.e., along magnetic poles).

Danger when theorists start looking at the same page

Theorists seem uninterested in why 35 years have passed with so little success. Not even interested enough when it can be shown that the favorite model is a cartoon model not based on real physics. The possible bad news here is that a number of other people have now become interested in how nonneutral plasmas impact our understanding of pulsars. Then everyone might have to learn this stuff!

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